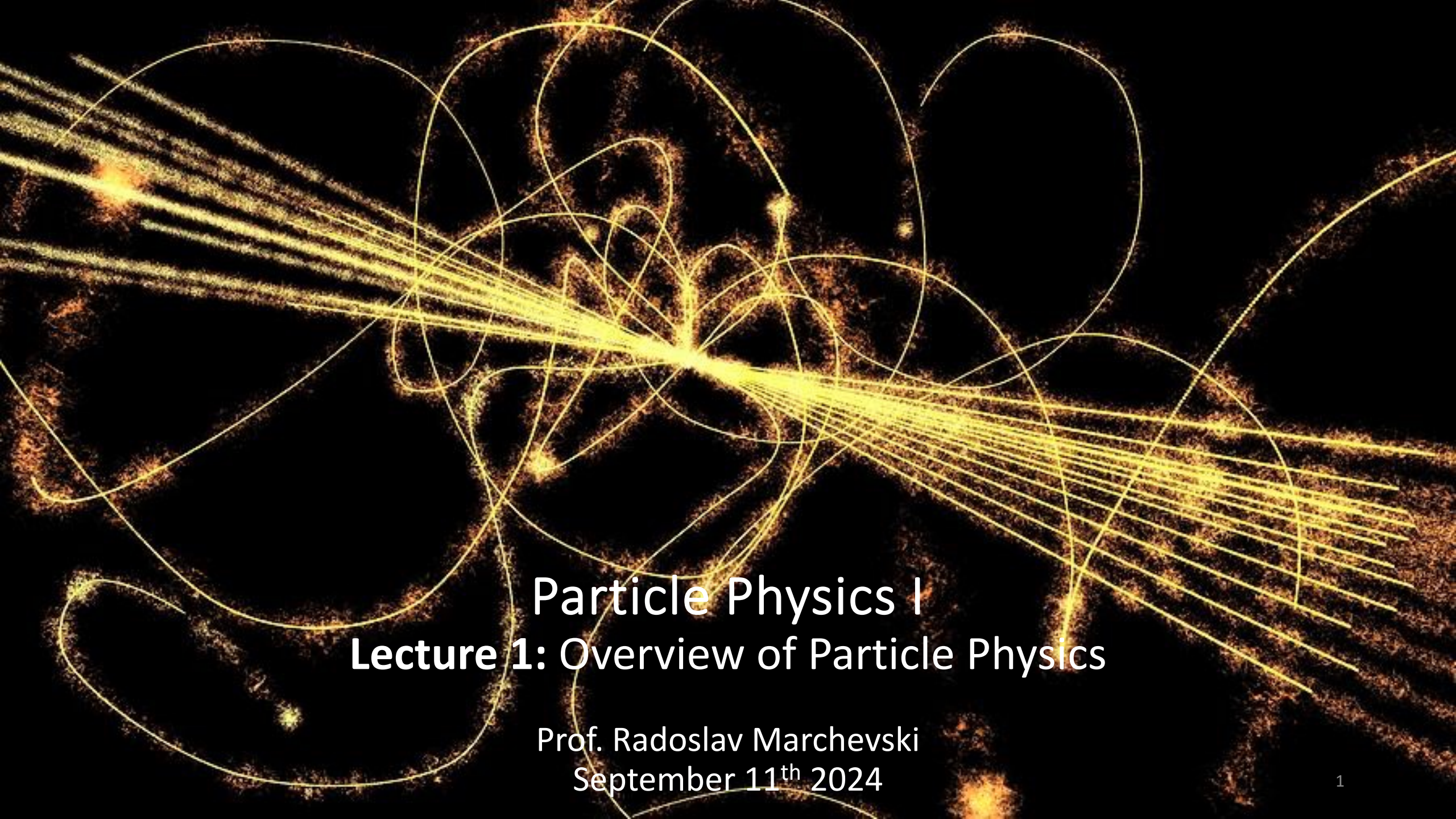


A visualization of particle tracks, likely from a bubble chamber or cloud chamber, showing numerous yellow and orange streaks against a black background. The tracks are complex, with many intersecting lines and loops, suggesting a high-energy collision event. The tracks are most concentrated in the center and spread out towards the edges.

Particle Physics I

Lecture 1: Overview of Particle Physics

Prof. Radoslav Marchevski
September 11th 2024

Practical information

- Lecturer: Radoslav Marchevski

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- Teaching assistant: Raphaël van Laak

web: <https://people.epfl.ch/raphael.vanlaak>

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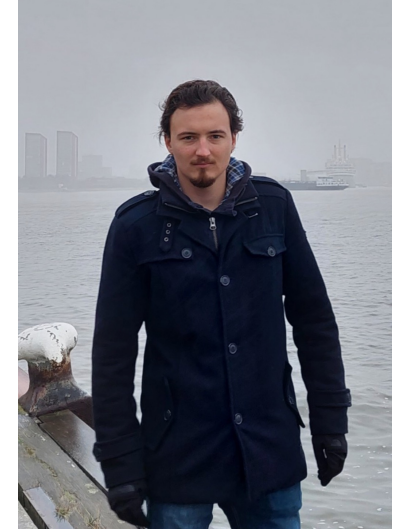
- Course material:

Moodle: <https://moodle.epfl.ch/course/view.php?id=14833>

will contain slides, exercises, and solutions

books: [Mark Thomson](#) “Modern Particle Physics” ([library](#))

Particle Data Group “The Review of Particle Physics” <https://pdg.lbl.gov/>



Provide regular feedback

- For each lecture & exercise session, you can share your feedback via moodle.
- Do not hesitate to talk to us after the lecture/exercise session or send us an email.

Reading list

The course closely follows the book by **Mark Thomson, "Modern Particle Physics" (2013)**, which is available at the EPFL library.

For summaries, most recent reviews and technical information, please use the Particle Data Group (PDG) website <https://pdg.lbl.gov/>.



FORUM

[Forum for Q&A on the lectures and exercises](#) 



FORUM

Announcements 



Course structure

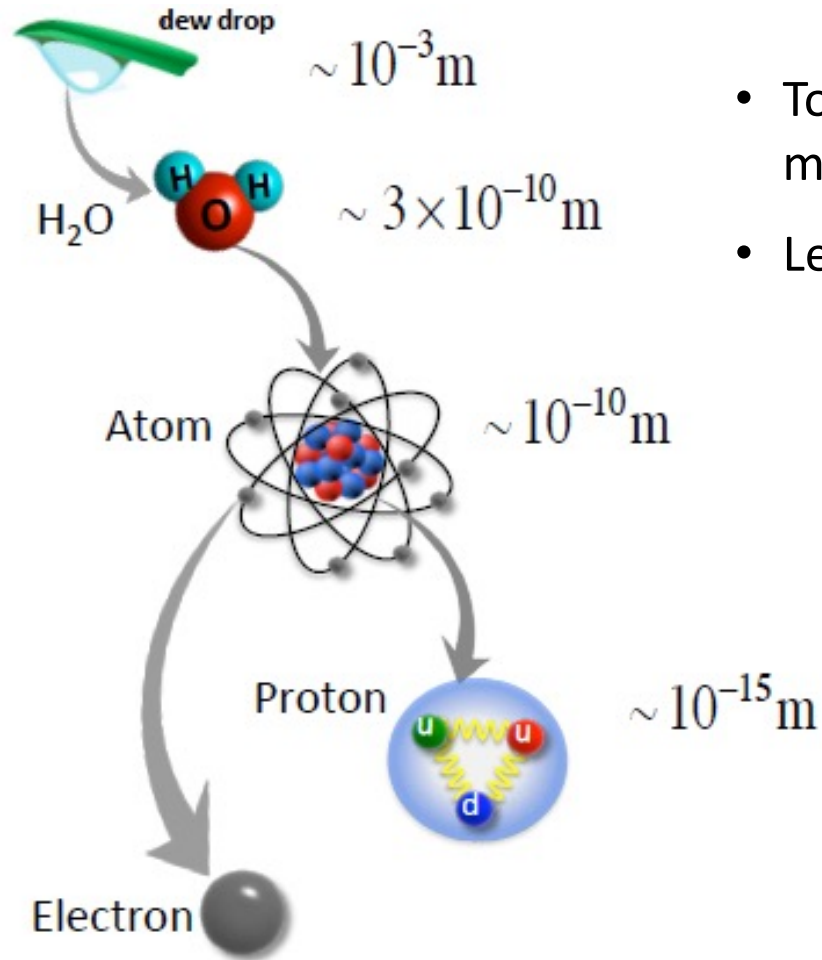
- Particle Physics I (this fall semester)
 - Overview, particle detection, accelerators
 - The Klein-Gordon and Dirac equations, spin
 - Interaction by particle exchange
 - QED: quantum electrodynamics
 - Symmetries and the quark model
- Particle Physics II (next spring semester)
 - QCD: quantum chromodynamics
 - The weak interaction
 - Electroweak unification and the W and Z bosons
 - The Higgs boson: theory and discovery
 - Dark matter and beyond-the-standard-model theories
- Particle Physics: the flavour frontier (next spring semester)
 - Symmetries of the Standard Model
 - Flavour and quark mixing
 - Spontaneous symmetry breaking and the Higgs boson
 - Experimental aspects of flavour physics
 - QCD at low energies
 - Rare decays
 - *CP* violation

Today's learning targets

- Introduction to particle physics
 - What are the constituents of matter and how are they organized?
 - How are particle interactions mediated?
 - Which interactions exist and what are their relative strengths?
 - What is the role of the Higgs boson and the Higgs mechanism?
 - Natural units
 - Feynman diagrams

Scope of particle physics

- Main questions that particle physics aims to address
 - what are the constituents of matter?
 - which are the forces holding them together to form matter?
 - is there a coherent and unified model or framework that describes everything that we observe?



- To study the “indivisible” constituents of matter we need to go down several many orders of magnitudes lower than what we are used to in our everyday life
- Let's take as an example the proton (not indivisible)
 - size/length scale (R) $\sim 10^{-15} \text{ m}$
 - mass (m) $\sim 10^{-27} \text{ kg}$
 - energy (mc^2) $\sim 10^{-10} \text{ J}$
 - time (R/c) $\sim 10^{-23} \text{ s}$

SI unit system used in everyday life is **not well-suited to describe phenomena at this level** $\Rightarrow$ **we need a more suitable system to rescale our units**

Natural units (Plank units)

- Measurement basis for everyday objects and macroscopic phenomena: [kg, m, s]
 - Not a *natural* choice for the properties of particles (e.g. $m_e = 9.1 \times 10^{-31} \text{ kg}$)
- Natural units: $[\text{kg}, \text{m}, \text{s}] \rightarrow [\hbar, c, \text{GeV}]$
 - Reduced Planck constant: $\hbar = 1.055 \times 10^{-34} \text{ J s} [\text{kg m}^2 \text{s}^{-1}]$
 - Speed of light in vacuum: $c = 2.998 \times 10^8 \text{ m s}^{-1}$
 - $1 \text{ GeV } (\sim m_p) = 10^9 \text{ eV} = 1.602 \times 10^{-10} \text{ J}$
- All quantities in particle physics can be expressed in GeV by choosing $\hbar = c = 1$
 - velocity is measured in units of c : $v \rightarrow v/c$
 - m, p and E measured in the same units [GeV]
 - Conversion from MeV to m: $\hbar c = 197 \text{ MeV fm } (1 \text{ fm} = 10^{-15} \text{ m})$
- Heaviside-Lorentz units: $\hbar = c = \epsilon_0 = \mu_0 = 1$
 - fine structure constant: $\alpha = \frac{e^2}{4\pi} \approx \frac{1}{137}$
- Gravitational and Boltzmann constants: $\hbar = c = \epsilon_0 = \mu_0 = G = k_B = 1$

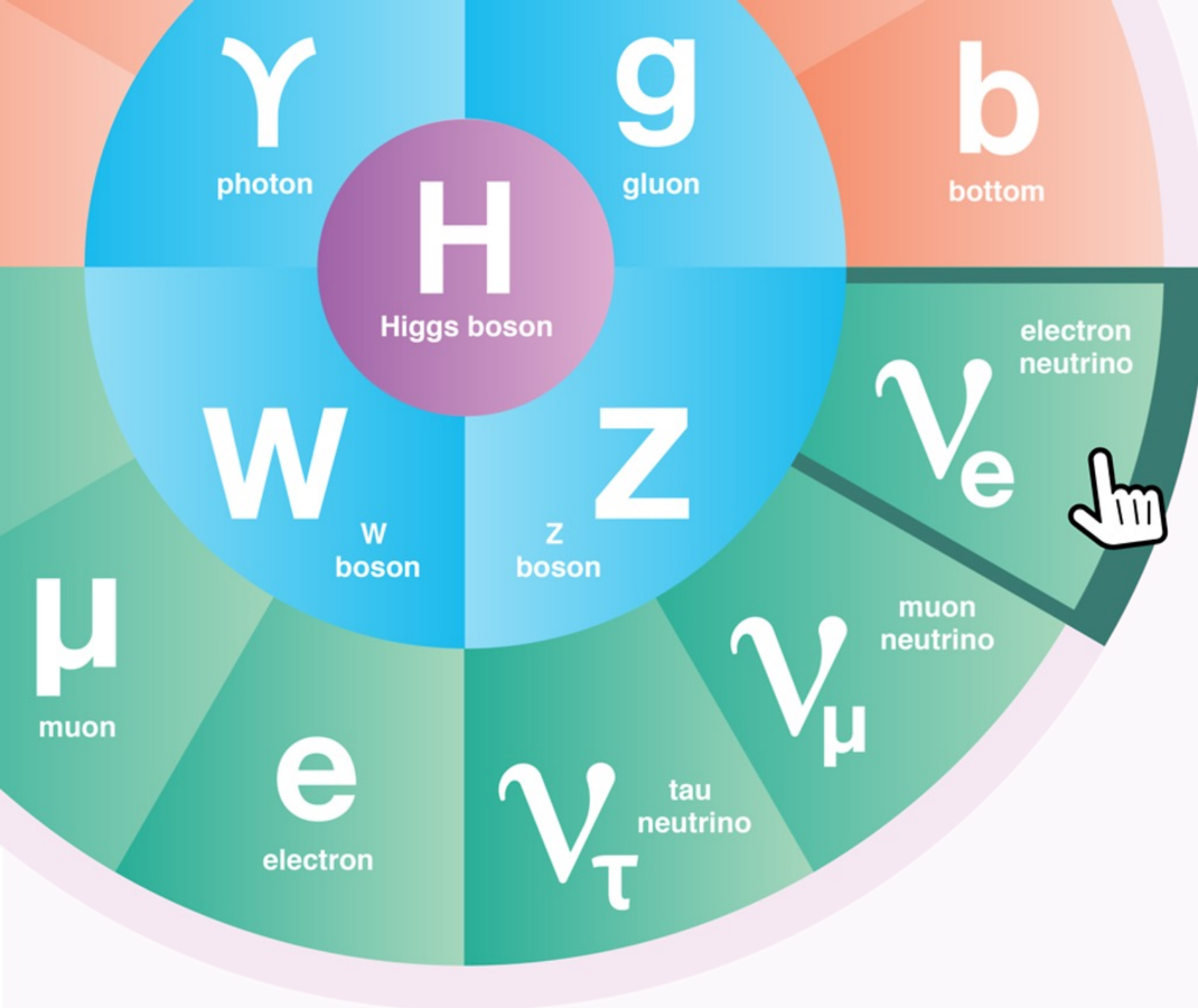
Natural units (Plank units)

Quantity	SI	Natural units	Conversion
Mass	kg	GeV	1 GeV = 1.8×10^{-27} kg
Length	m	1/GeV	1 GeV ⁻¹ = 0.197×10^{-15} m
Time	S	1/GeV	1 GeV ⁻¹ = 6.58×10^{-25} s
Energy	kg m ² /s ²	GeV	1 GeV = 1.602×10^{-10} J
Momentum	kg m/s	GeV	1 GeV = 5.39×10^{-19} kg m/s
Force	kg m/s ²	GeV ²	1 GeV ² = 8.19×10^5 N
Area (cross section)	m ²	1/GeV ²	1 GeV ⁻² = 0.389 mb = 0.389×10^{-31} m ²
Charge	C = A s	none	1 = 5.28×10^{-19} C $e = 0.303 = 1.602\times10^{-19}$ C

- Correct unit dimensions to derive the numbers in the table:

Energy	GeV	Time	$(\text{GeV}/\hbar c)^{-1}$	$c = 2.998 \times 10^8 \text{ m/s}$ $\hbar = 1.055 \times 10^{-34} \text{ J s}$
Momentum	GeV/c	Length	$(\text{GeV}/\hbar c)^{-1}$	
Mass	GeV/c^2	Area	$(\text{GeV}/\hbar c)^{-2}$	

- These conversions are rarely needed in practice: we will use GeV throughout the course



explore

The Standard Model

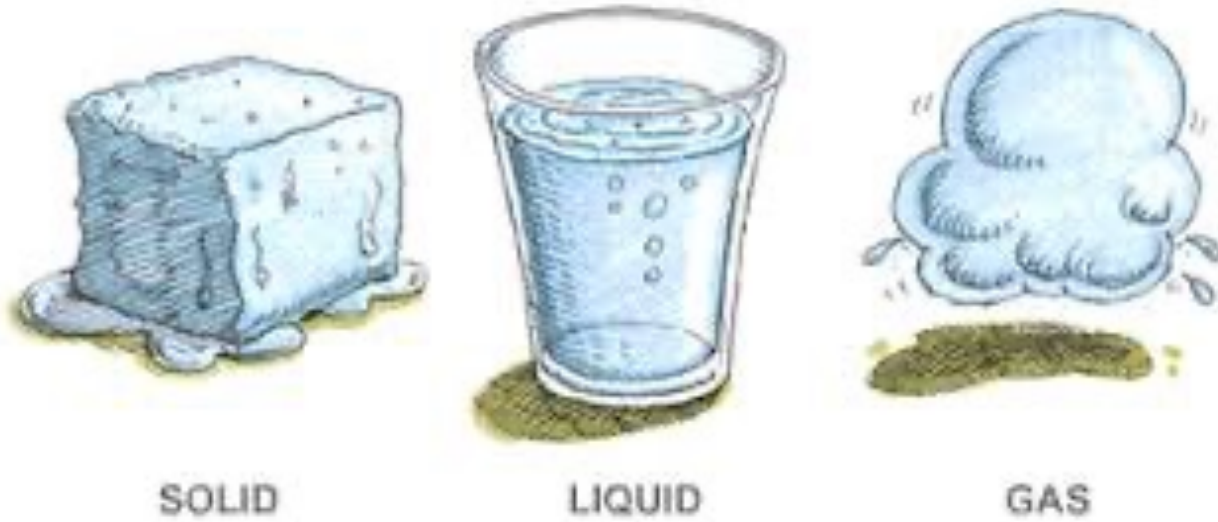
-
- QUARKS
 - LEPTONS
 - BOSONS
 - HIGGS BOSON

Elementary particle physics

- Particle physics is the study of:
 - **Matter:** the *“fundamental”* building blocks of the universe – elementary particles
 - **Force:** the *“fundamental”* interactions between the elementary particles
- Try to categorise the particles and the interactions between them in as simple and fundamental manner as possible

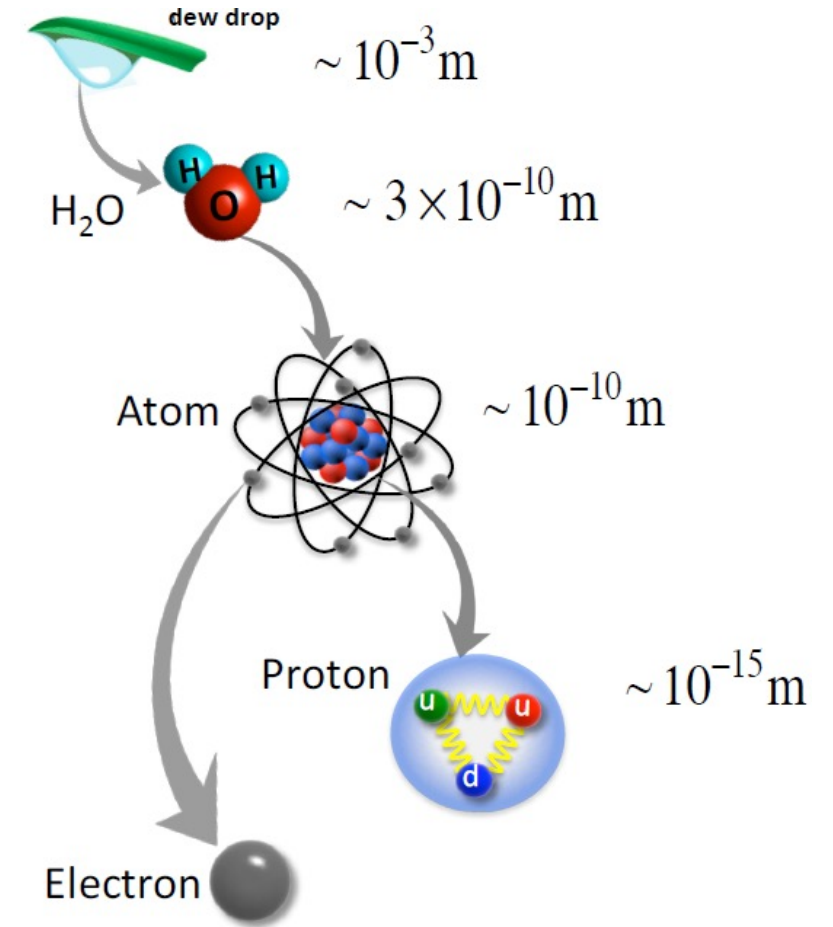
Elementary particle physics: Matter

What people usually imagine when hear *matter*



- Fundamental constituents of ordinary matter
 - leptons (e.g. *electron*)
 - Quarks (e.g. *up* and *down* quarks, making up the protons and neutrons)
- Leptons and quarks are called **fermions**: particles with $\frac{1}{2}$ (half-integer) spin

What matter is down to its constituents



Known matter

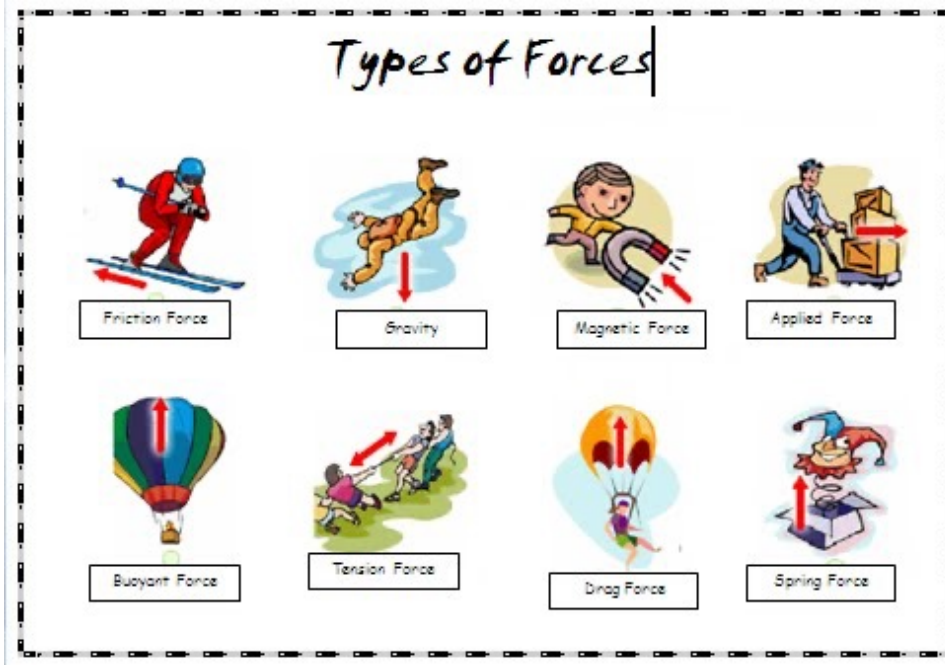
Generation		Leptons			Quarks			
	particle		Q	m/GeV	particle		Q	m/GeV
1 st	electron	e^-	-1	0.0005	down	d	$-1/3$	0.005
1 st	neutrino	ν_1	0	$< 10^{-9}$	up	u	$+2/3$	0.003
2 nd	muon	μ^-	-1	0.106	strange	s	$-1/3$	0.1
2 nd	neutrino	ν_2	0	$< 10^{-9}$	charm	c	$+2/3$	1.3
3 rd	tau	τ	-1	1.78	bottom	b	$-1/3$	4.2
3 rd	neutrino	ν_3	0	$< 10^{-9}$	top	t	$+2/3$	173

Known matter

Generation			Leptons		Quarks			
	particle		Q	m/GeV	particle		Q	m/GeV
1 st	electron	e^-	-1	0.0005	down	d	$-1/3$	0.005
1 st	neutrino	ν_1	0	$< 10^{-9}$	up	u	$+2/3$	0.003
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3 rd	neutrino	ν_3	0	$< 10^{-9}$	top	t	$+2/3$	173

- “Matter” is described by **point-like spin-½ fermions**
- Anti-particles have the same mass as particles (in the table) but with opposite charge
- Three generations of quarks/leptons: copies of each other, only differing in mass
 - **We don't know why exactly three generations**
- Neutrinos are much lighter than all other particles (**$< 1\text{eV}$**)
 - We know that neutrinos can't be massless because of neutrino oscillations
 - **We don't know why the neutrino masses are so small**

Elementary particle physics: Forces



- Four fundamental interactions between elementary particles
- The forces are transmitted to the matter particles by means of mediator particles: **bosons** (particles with integer spin)
- The gravitational force **is not included** in the Standard Model
 - Force between individual particles extremely small and can be neglected in the discussion of particle interactions



Electromagnetic

Photon

Atoms
Light
Chemistry
Electronics

Weak

Bosons (W,Z)

Neutron decay
Beta radioactivity
Neutrino interactions
Burning of the sun

Strong

Gluons (8)

Quarks

Mesons
Baryons

Nuclei

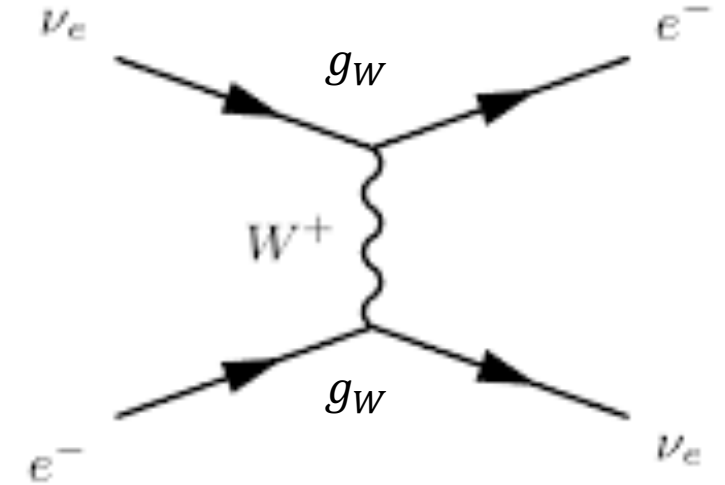
Gravitational

Graviton ?

Solar system
Galaxies
Black holes

Known forces

Force	Strength	Bosons		Spin	m/GeV
Strong	1	8 gluons	g	1	0
Electromagnetic	10^{-3}	Photon	γ	1	0
Weak	10^{-8}	W boson	$W^\pm$	1	80.4
		Z boson	Z	1	91.2
Gravitational	10^{-37}	Graviton?	G	2	0



Note: interaction strength only indicative – it depends on the considered distance and energy scales

- Strength of the fundamental interaction represented by the charge g
- Related to the **dimensionless** coupling “constant” α , e.g. QED
 - In SI $g_{em} = e = \sqrt{4\pi\alpha\epsilon_0\hbar c}$
 - In natural units: $g_{em} = \sqrt{4\pi\alpha}$
- Convenient to express couplings in terms of α
 - α is dimensionless and does not depend on the system of units (not true for the numerical value of e)

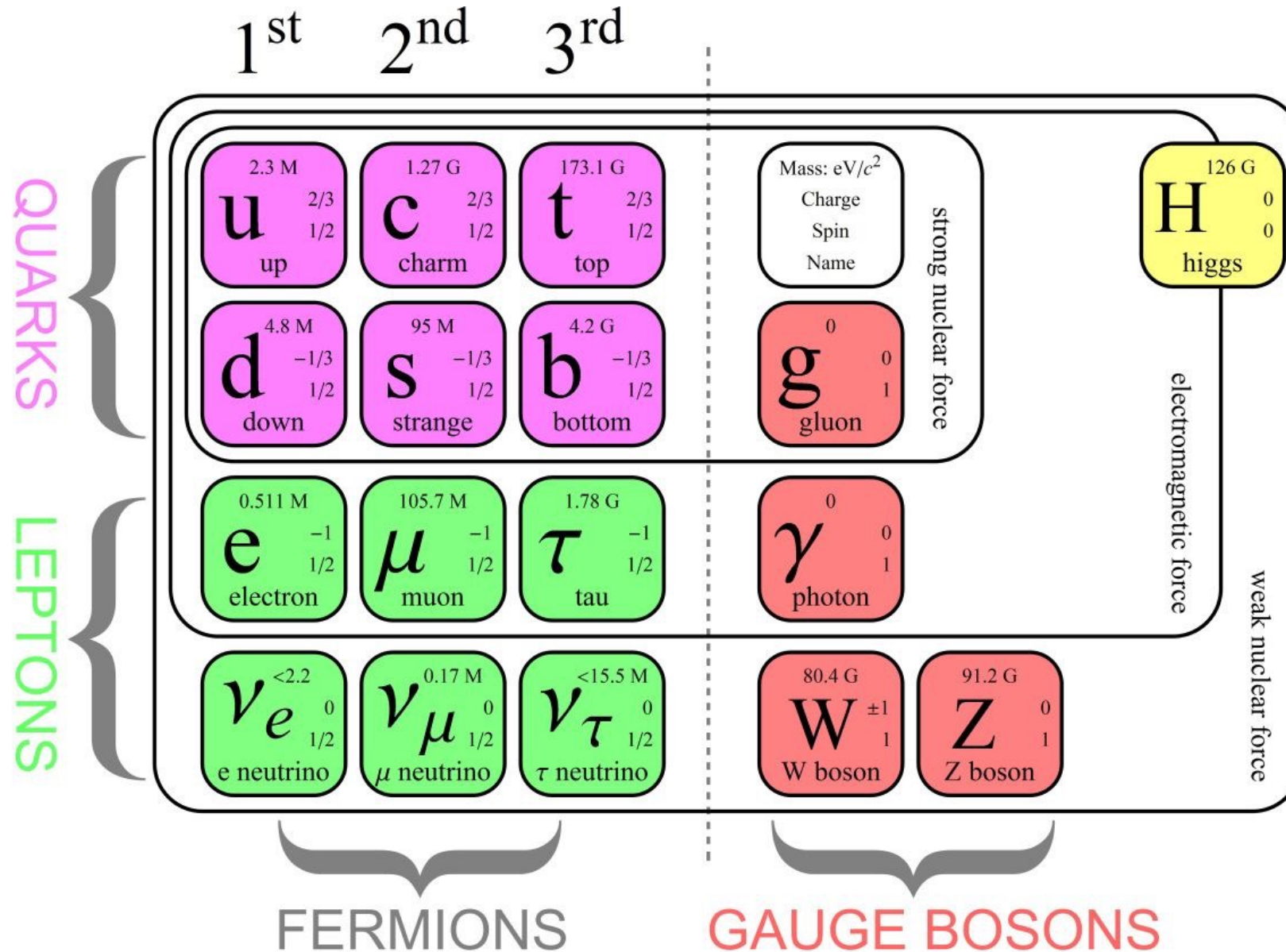
The Higgs boson

- Final element of the Standard Model of particle physics: $m_H \approx 125\text{GeV}/c^2$ particle discovered in 2012 by the CMS in ATLAS collaborations at the LHC
- The Higgs boson is **different** from most fundamental particles in the Standard Model
 - **fermions**: particles with spin $\frac{1}{2}$
 - **gauge bosons**: particles with spin 1
 - **Higgs boson**: **fundamental scalar particle with spin 0 (the only one discovered to date)**
- The Higgs boson provides a mechanism (non-zero Higgs field) by which all fundamental particles acquire mass
- **Note**: proton and neutron masses are largely due to binding energy (don't directly come from the Higgs boson)

The Standard Model (SM)

- The Standard Model (SM) of particle physics describes three of the four known fundamental forces in the universe and classifies all known elementary particles
 - Theory combining quantum mechanics and special relativity $\Rightarrow$ relativistic quantum field theory
 - 19 free parameters related to quarks, charged leptons, and gauge bosons (26 if we include ν masses/mixing parameters)
 - Global Poincare symmetry (translation, rotation, change of reference frame from special relativity)
 - Local $SU(3) \times SU(2) \times U(1)$ gauge symmetry $\Rightarrow$ gives rise to the strong, electromagnetic, and weak interactions
- Many indications that the SM is not the final theory: still many mysteries and open questions left unanswered
- The SM does not describe gravitational interactions
 - Negligible on atomic and sub-atomic length scales ($10^{-10} - 10^{-18}$ m)
 - Relevant close to the Planck scale: $l_P = \frac{\sqrt{\hbar G}}{c^3} \approx 10^{-35}$ m (far away from current experimental sensitivity)

The Standard Model (SM)



Elementary particles and their interactions

electric charge:

0

-1

$-1/3$

$2/3$

First generation

ν_e

e^-

d

u

Second generation

ν_μ

μ^-

s

c

Third generation

ν_τ

τ^-

b

t

H:
Higgs

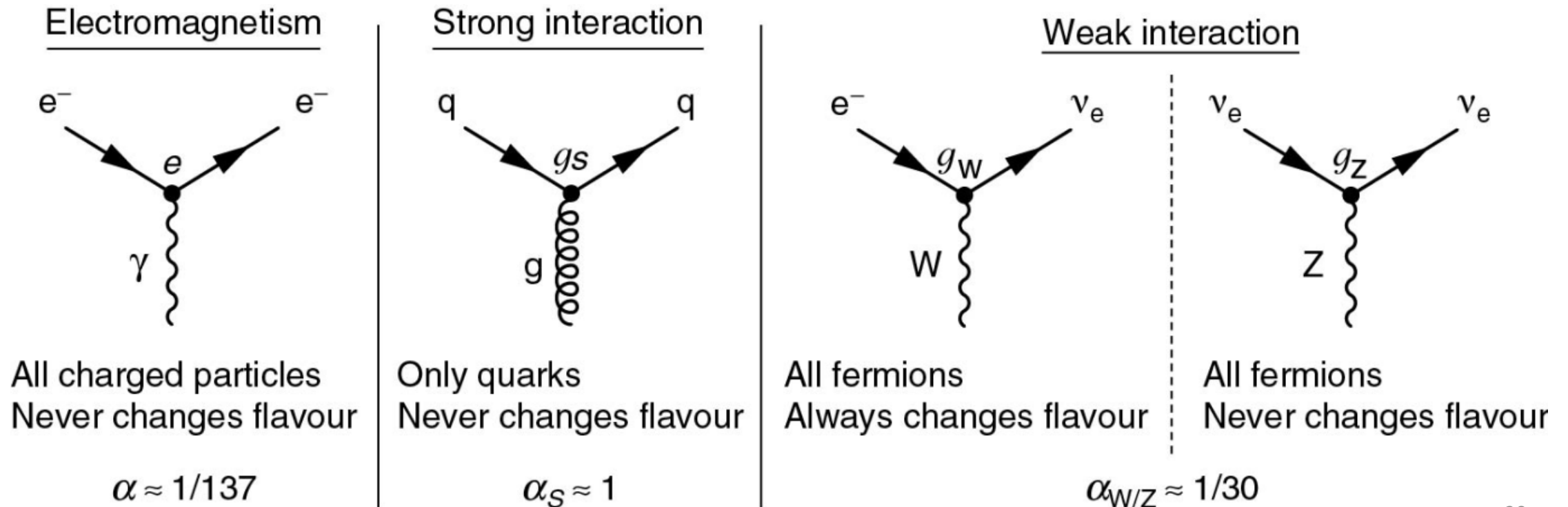
$W^\pm, Z$:
weak

γ :
electromagnetic

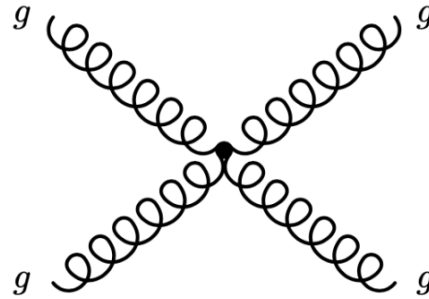
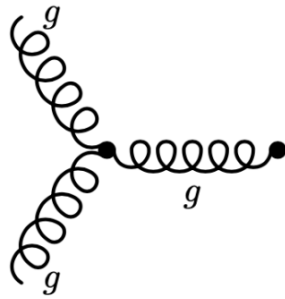
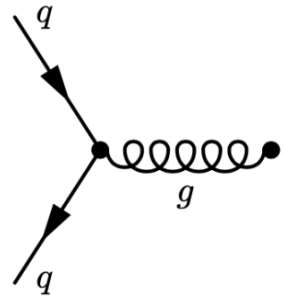
g:
strong

Standard Model vertices

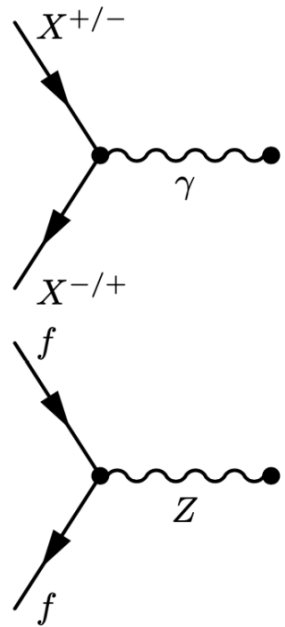
- The coupling of the force-carrying gauge bosons to the fermions is represented by the SM interaction vertices
- Three-point vertex of the gauge boson and an incoming and outgoing fermion
- A particle couples to a force-carrying gauge boson only if it carries the charge of the interaction



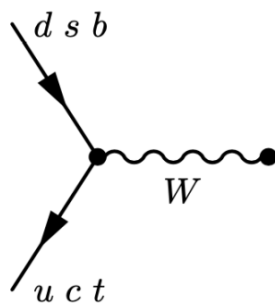
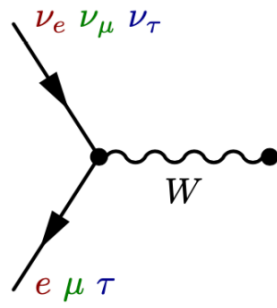
All Standard Model vertices



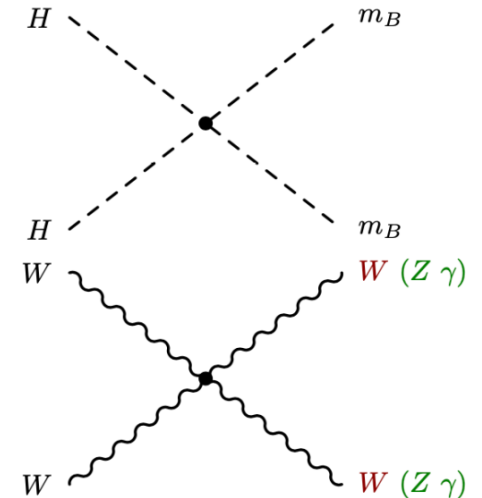
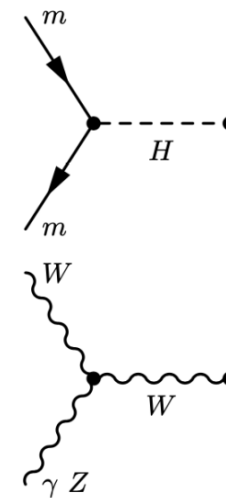
strong interaction



EM interaction



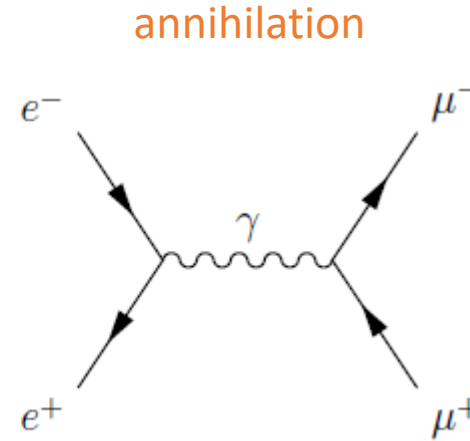
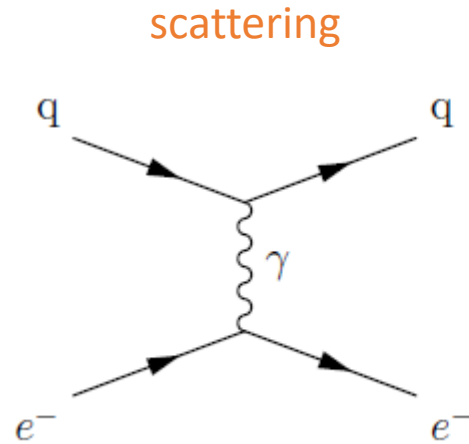
weak interaction



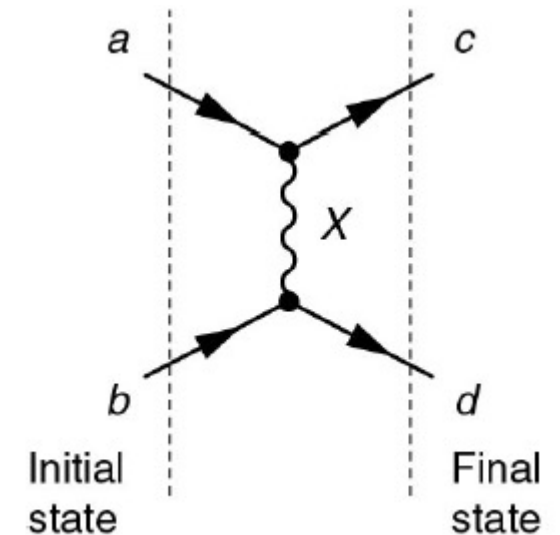
Higgs, EWK

Feynman diagrams

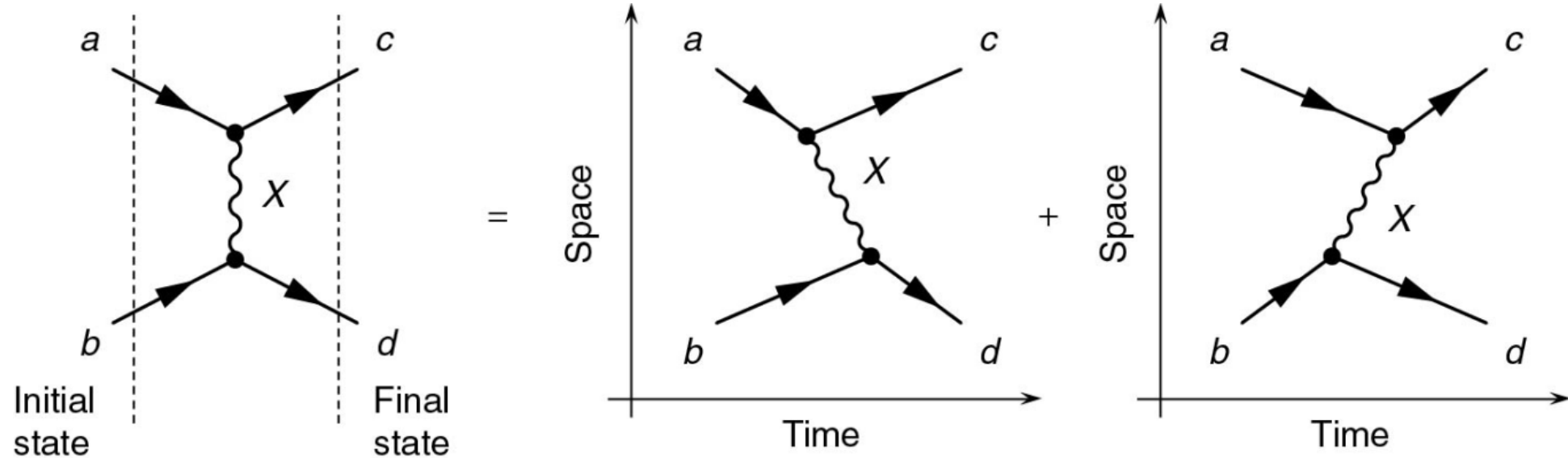
- Particle interactions can be represented as Feynman diagrams:



- “Time” in the diagrams runs from left to right only in a sense that
 - Left-hand side of the diagram represents the **initial state**
 - Right-hand side of the diagram represents the **final state**
 - Central part shows the **particles exchanged** and the **SM vertices involved**
- Negative “time” arrows correspond to anti-particles
- Energy, (angular) momentum, etc. **conserved at all interaction vertices**
- All intermediate particles are “virtual” : $E^2 \neq p^2 + m^2$



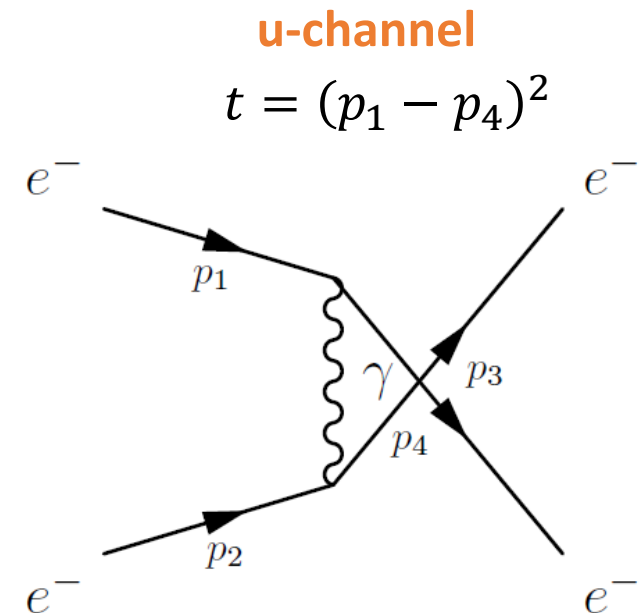
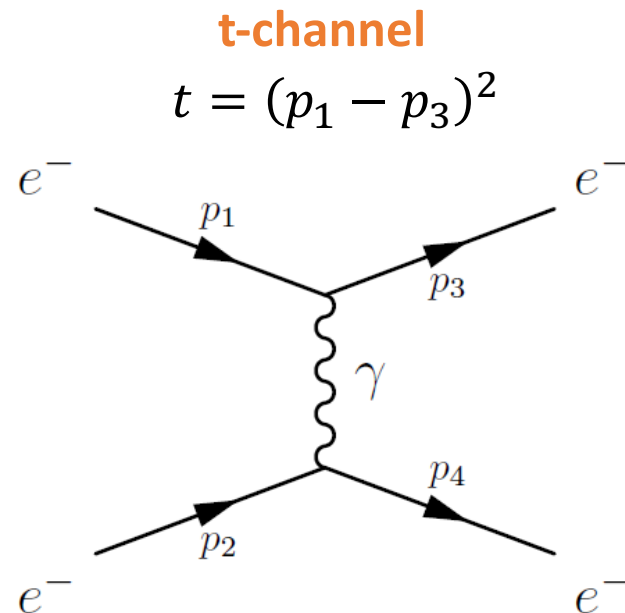
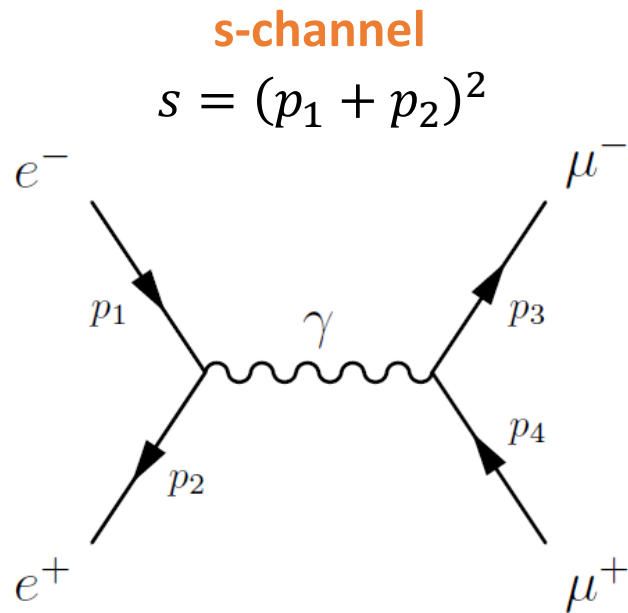
Feynman diagrams



- Generic Feynman diagrams much more than pictorial representation of the fundamental physics underlying a process
 - represents the sum of the quantum-mechanical amplitudes for all possible time orderings (we can only observe initial and final states)
- Once the Feynman diagram is drawn, it is straightforward to write down the transition matrix element using the relevant Feynman rules $\Rightarrow$ avoid the need to calculate each process from first principles in Quantum Field Theory
- In principle, for each process considered there will be infinite number of diagrams
 - We will concern ourselves only with the simples (lowest order) Feynman diagrams for a given process – higher order diagrams are suppressed by higher orders of the coupling constants involved in the interaction

Mandelstam variables s, t, and u

- In particle scattering/annihilation there are three particularly useful Lorentz-invariant quantities: **s**, **t**, and **u**
- Consider a scattering process $1 + 2 \rightarrow 3 + 4$
- (Simple) Feynman diagrams can be categorized according to the four-momenta of the exchanged particles

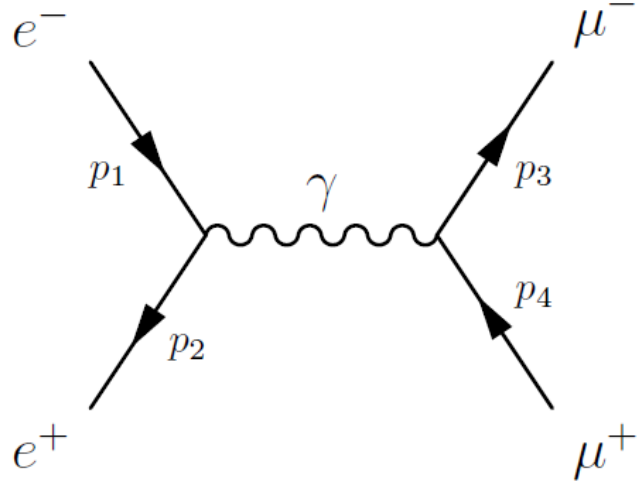


$$s + t + u = m_1^2 + m_2^2 + m_3^2 + m_4^2$$

Note: u-channel diagram only if the final state particles are indistinguishable

Example: Mandelstam s

- Centre-of-mass energy **s**:



$$s = (p_1 + p_2)^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$

- A scalar vector product of two four-vectors $\Rightarrow$ Lorentz-Invariant quantity $\Rightarrow$ valid for any frame of reference
- Choose the most convenient (center-of-mass) frame: $p_1 = (E_1, \vec{p}), p_2 = (E_2, -\vec{p}) \Rightarrow s = (E_1 + E_2)^2$
- **$\sqrt{s}$ is the total collision energy in the centre-of-mass frame**

From Feynman diagrams to physics

- Particles physics involves the building of theories of fundamental particles and their interactions and testing their predictions against experimental data
 - dealing with fundamental particles and make precise theoretical predictions – not complicated by dealing with many-body systems
 - many beautiful experimental measurements: **precise theoretical predictions challenged by precise measurements**
 - For all its flaws, the SM describes “all” experimental data $\Rightarrow$ one of the most remarkable achievements of the 20th century
- Requires understanding of both theory and experimental data
 - first part of the course: Feynman diagrams mainly used to describe how particles interact
 - second part of the course: use Feynman diagrams and their associated rules to perform calculations of some processes

Summary of first lecture

Main learning outcomes

- What is the scope of particle physics
- What are the fundamental matter particles, how they interact, and which bosons are mediate their interactions
- How to describe particle kinematics
- How to describe particle interactions with Feynman diagrams